

Formation of bulges in very late-type galaxies from SSCs

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ABSTRACT

The dynamical evolution of super star clusters (SSCs) moving in the background of a dark matter halo has been investigated as a possible event responsible for the formation of bulges in late-type spirals. The underlying physical processes include sinking of SSCs due to the dynamical friction and stripping of SSCs on their way to the center. Our model calculations show that only sinking of circumnuclear SSCs contributes to the formation of galactic bulges at the early stage. Based on the assumption of a universal density profile for the dark matter halo, and an isothermal model for the SSCs, our simulations have yielded bulges that are similar in many aspects to the observational ones. In particular, the derived surface density profiles can be well fitted by an exponential structure with nuclear cusps, which is consistent with HST observations.

Key words: galaxies: bulge – galaxies: kinematics and dynamics

1 INTRODUCTION

Bulges are basic building blocks of the Hubble sequence, as shown from the studies on the growth of galactic bulges by mergers (e.g. Walker et al. 1996; Agueri et al. 2001), or by secular evolution (e.g. Norman et al. 1996; Zhang 1999). It is important to understand whether these processes could push late-type spirals across the Hubble sequence toward early-type spirals.

Also, studies show that elliptical galaxies, which are thought to be similar to the bulges of early-type spirals, can be formed through mergers of spirals with similar masses (e.g. Barnes & Hernquist 1991).

A significant amount of data on bulges have been accumulated (e.g. Andredakis et al. 1995; Carollo 1999; Seigar et al. 2002), with a common perception of $R^{1/4}$ and exponential bulges for early- and late-type spirals, respectively. Among them, the HST survey of early- to intermediate-type spirals (Carollo 1999, C99 hereafter) has yielded new insight into the nuclear region of these systems.

The most interesting results from this survey are that 11 of the 12 S0a - Sab galaxies display $R^{1/4}$ bulges, while 14 out of the 20 Sb - Sc galaxies have exponential bulges. The majority of these bulges illustrate nuclear cusps, steeper ones for $R^{1/4}$ structures and shallower for exponential bulges. C99 argued convincingly that the shallower cusps in exponential bulges are of stellar origin, and claimed that they are the old end of star clusters with masses of about $10^6 M_\odot$.

Probably consistent with this argument is an evolved super star cluster (SSC) located in the nucleus of M33 (Kormendy & McClure 1993). The occurrence of old-end star clusters at the nuclei of galaxies has been reported in other two nearby Sc galaxies, NGC 247 and NGC 2403 (Davidge & Courteau 2002). In fact, nuclear star clusters may be a common phenomenon (e.g. Davidge & Courteau 2002; Böker et al. 1999, and references therein) in late-type galaxies. Possibly related to the existence of nuclear star clusters is the presence of circumnuclear young massive star clusters, or circumnuclear SSCs (e.g. Larsen & Richtler 1999; Whitmore et al. 1999; Meylan 2001).

A question then arises whether there is a physical relation between these two common phenomena in late-type spirals, i.e., the common existence of nuclear/circumnuclear star clusters and the exponential bulges with nuclear stellar cusps. If this is the case, what is the physical process responsible for this relation? A prevailing view for the formation of bulges in late-type galaxies is the secular evolution of disks due to the bar formation/destruction (e.g. Pfenniger & Norman 1990; Norman, Sellwood, & Hasan 1996). However, Bureau argued in his review (2002) against this scenario based on the consideration of the fast duty cycle of the bar formation/destruction, inferred from the omnipresence of bars (Seigar & James 1998).

In this paper we report our study, motivated by Carollo's claims and the observations

mentioned above, on the dynamical evolution of circumnuclear SSCs moving in the dark matter halo as a possible process for the formation of bulges with nuclear cusps in very late-type galaxies.

It has been suggested (e.g., Tremaine et al. 1975) that the dynamical friction acting on globular clusters moving on orbits near the centre of a galaxy would lead to the formation of a nucleus. The underlying physical processes in our scenario, however, are sinking of SSCs due to the dynamical friction and tidal stripping of SSCs on their way to the center. The inclusion of tidal stripping, which is not considered in the previous work, is crucial in producing an exponential bulge with nuclear stellar cusp.

2 MODELS

2.1 SSC model

Recent high resolution observations of starburst galaxies have revealed the existence of many compact, young, and very luminous SSCs in the central regions of galaxies (Surace & Sanders 1999, Scoville et al. 2000, de Grijs et al. 2001). Numerical simulations (Mihos & Hernquist 1996, Barnes & Hernquist 1996) have also shown that interaction or merger among galaxies can trigger strong starbursts around the nuclear regions. While galaxies are merging or interacting, some gas components could lose their angular momentum and fall into the central region. High pressure of the warm interstellar gas could induce global collapse of giant molecular clouds and thus form circumnuclear SSCs (Jog & Solomon 1992, Harris & Pudritz 1994).

Although there is already a body of observational data on SSCs, their dynamical properties are not yet well understood. SSCs are believed to be the progenitors of present-day globular clusters (GC, e.g. Origlia et al. 2001). It seems reasonable to model SSCs, then, in light of this situation.

Based on the analogy with GCs, we assume that SSCs have a similar mass spectrum as the initial GC mass function but with larger mean value. According to Vesperini (2000,2001), the log-normal mass function for SSCs (SSCMF) can be written as

$$\text{Log}_{10}\left(\frac{M}{M_{\odot}}\right) \sim N(\exp(\text{mean}) = 2 \times 10^6 M_{\odot}, \text{variance} = 0.08) \quad (1)$$

where the mean value is chosen by the following consideration. Model calculations indicate (e.g., Takahashi & Portegies Zwart 2000) that compact SSCs with steep IMFs survive large

mass loss (more than 90% of their initial masses) and thus are the most likely progenitors of GCs. Considering the mean GC's mass of about $1 - 2 \times 10^5 M_\odot$, we may infer the mean SSC's mass of about $2 \times 10^6 M_\odot$. The measured masses of SSCs detected in NGC4038/39 are consistent with this prediction, being in the range of $6.5 \times 10^5 - 4.7 \times 10^6 M_\odot$ (Mengel et al. 2001), and 4 out of 5 clusters have masses larger than $2 \times 10^6 M_\odot$.

Using the above-mentioned SSCMF, we generate randomly 100 sets of SSCs, each containing 100 SSCs (comparable to the number observed by Fellhauer 2001 and Whitmore et al. 1999). For simplicity, the SSC is modeled as a truncated isothermal sphere with three parameters: the central density (ρ_c), the velocity dispersion (σ), and the initial truncated radius (R_0). Taking a range of ρ_c between $5.3 \times 10^3 M_\odot/pc^3$ and $3.4 \times 10^4 M_\odot/pc^3$ (Larsen et al. 2001, Campbell et al. 1992), we assume a linear function of cluster mass, M , for $\rho_c(M)$. And with R_0 taken to be the local tidal radius, σ can be derived from M and ρ_c .

According to the observational results of NGC1156, NGC1313, and NGC5236 (Larsen & Richtler 1999), the number of circumnuclear SSCs is approximately proportional to $\frac{1}{R}$, where R is the projected distance from the galactic center. We assume that the SSCs are distributed over the range of $0.4 - 6.4 kpc$ (Larsen & Richtler 1999). All SSCs are assigned a local circular speed.

2.2 Background

In general, small galaxies appear to be dominated by dark matter (DM) even in their inner regions (e.g. Marchesini et al. 2002, Wilkinson et al. 2002, and references therein). In particular, due to their bulge-less appearance and large mass-to-light ratio, very late-type spirals are thought to be dark-matter-dominated at all radii. Analyses of high resolution H_α rotation curves, in combination with accurate HI rotation curves, confirms that late-type spirals are completely dominated by dark matter (Persic et al. 1996, Marchesini et al. 2002). Therefore, considering the bulge-formation process in very late-type galaxies (Sdm type and later) we only take a dark matter halo as the initial background. For the dark halo, we assume the universal density profile (Navarro et al. 1997, hereafter NFW), which can be written as (e.g., Binney & Merrifield, 1998)

$$\rho_h(r) = \frac{M_{0h}}{r(a_h + r)^2} \quad (2)$$

where r is the distance from the halo center.

As the halos evolve, their growth can have effect on the bulge formation process. Here we restrict our study to determining if the mechanism works for SSCs formed in halos at different evolutionary stages. We will focus on a time scale of 1 Gyr so that we can neglect the evolution of the halo. We consider two halos with quite different masses: a large one with mass $M_{200} = 10^{12}h^{-1}M_{\odot}$ (Y.P. Jing, private communication) and a smaller halo with mass $M_{200} = 3 \times 10^{11}M_{\odot}$. Further, we assume a Hubble constant $H_0 = 75\text{kms}^{-1}\text{Mpc}^{-1}$, $h = 0.75$ and a ΛCDM cosmological model (Jing, 2000). Then the NFW halos are determined via the scaling law (see Table 1).

Table 1. Parameters of the chosen NFW halos

$M_{200}(M_{\odot})$	$r_{200}(kpc)$	c	$a_h(kpc)$	$M_{0h}(M_{\odot})$
$10^{12}h^{-1}$	216.8	8.5	25.5	7.8×10^{10}
3×10^{11}	131.9	10	13.2	1.6×10^{10}

While the mass outside several hundred pc s remains dominated by a dark halo, the mass within $100pc$ can be significantly changed by the fallen SSCs together with their stripped mass. In order to account for this effect, we add a spherical component, represented by shells of equal density, which varies according to the changing SSC mass contribution.

2.3 Dynamical friction

We define M and \vec{V}_M (with $V_M = |\vec{V}_M|$) equal to, respectively, the mass and velocity of cluster experiencing the dynamical friction. Assuming the background matter has a Maxwellian velocity distribution with dispersion σ_{bgd} , and is composed of particles with mass much smaller than M , the dynamical friction formula may be written as (e.g., Binney & Tremaine, 1987)

$$\frac{d\vec{V}_M}{dt} = -\frac{2\pi \log(1 + \Lambda^2)G^2 M \rho}{V_M^3} [\text{erf}(X) - \frac{2X}{\sqrt{\pi}} \exp(-X^2)] \vec{V}_M \quad (3)$$

where erf is the error function, and,

$$\begin{cases} \Lambda = \frac{b_{max} V_{typ}^2}{GM} \\ X = \frac{V_M}{\sqrt{2}\sigma_{bgd}} \end{cases} \quad (4)$$

The quantity b_{max} is the so-called maximum impact parameter and V_{typ} a typical measure of the relative velocity between M and a background particle. Neither b_{max} nor V_{typ} is precisely defined. Fortunately, uncertainty in either quantity causes no significant difference

in the resulting value of the dynamical friction. Following Binney & Tremaine (1987), we use $b_{max} \equiv 2kpc$ and take $V_{typ} \equiv V_M$. The velocity dispersion $\sigma_{bkgd}(r)$ can be roughly estimated from the Jeans equation.

2.4 Stripping

We assume that the stellar mass outside a sphere of radius R_t , which corresponds to the instantaneous Hill stability region around the SSC center, will be stripped. Since stripping goes on continuously as r (the distance between halo and SSC centers) decreases, only a thin outer layer is stripped at a time. On average, the stars stripped when the SSC goes from r to $r - dr$ contribute to a region radially bounded by $r + R_t(r)$ and $r - dr - R_t(r - dr)$. As a first-order approximation, the mass of the stripped stars is considered to be, at some later epoch, uniformly distributed in the shell bounded by $r + R_t(r)$ and $r - dr - R_t(r - dr)$. By summing up all of the stellar mass stripped at various rs , the stripped stellar mass distribution can be derived.

If a single massive object is embedded in the center of an SSC, stripping cannot proceed further when only this object is left. X-ray observations show many so-called super-Eddington sources associated with SSCs (Matsumoto et al. 2001, Strikland et al. 2001). It is not yet clear whether the observations indicate intermediate-mass black holes (IMBHs, ranging from several hundreds to about one thousand solar masses, Ebisuzaki et al. 2001) or are due to the beam effect (King et al. 2001). If massive black holes do form in SSCs, they would most likely be at the center. Therefore, in our simulations, we consider two extreme cases: stripping is not allowed when the mass of the stripped SSC is less than $1M_\odot$ and $1000M_\odot$, respectively.

3 RESULTS

Figure 1 shows the surface density profiles of simulated individual galaxies with high-density central components formed at 1 Gyr (with a proportion of about 65% and 90% for the larger and smaller halos, respectively). Comparing our simulations with the results of the HST survey by Carollo et al. (1999) is very instructive. Among their surveyed sources, 13 galaxies are of Hubble types Scd and later. For these galaxies (at distances greater than 13 Mpc) the smallest area the HST can resolve is 5 pc from the center. About 50% of the 13 galaxies contain exponential bulges with central stellar clusters. The remaining ones do not

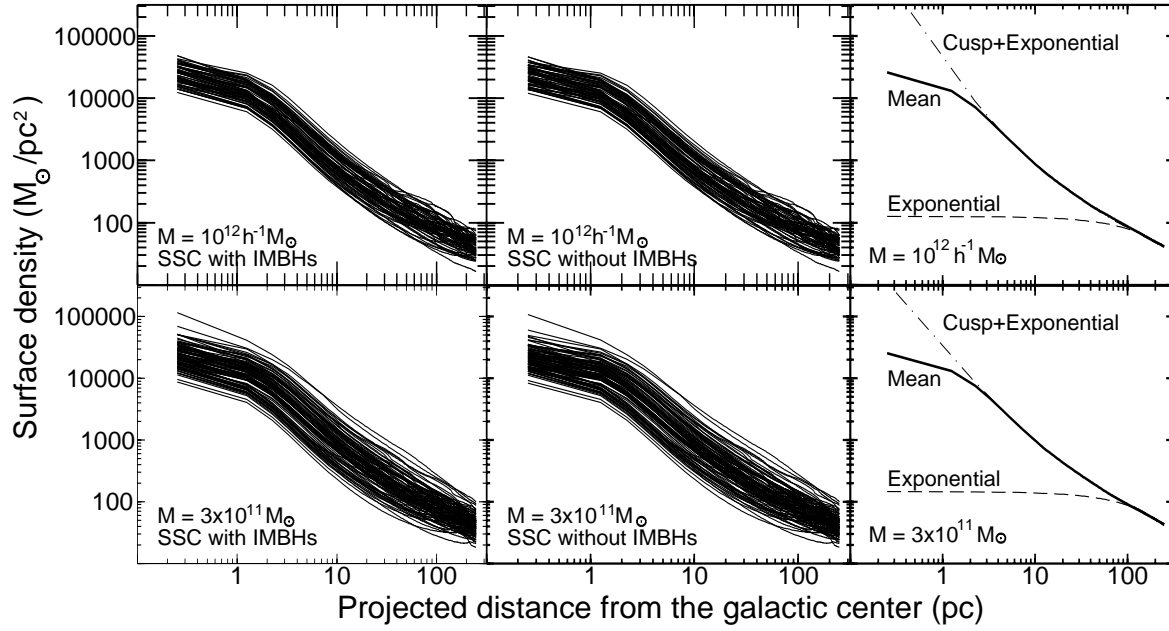


Figure 1. Surface densities derived by SSCs with/without IMBHs for two DM density profiles adopted. The mean surface density profiles illustrated in the right two panels are derived from the models without IMBHs.

have accurate fits, though some of them display central cusps. Our mean model profiles (also in Fig.1) share some characteristics with the above observational results, i.e., the general presence of resolved compact clusters on top of the exponential bulges.

In order to give a quantitative comparison with the observations, following Carollo et al., we first fit the outer part of the mean profile with an exponential model. We then subtract this model of the exponential bulge, leaving the cusp component. This, in turn, is fit with the cusp model of Carollo & Stiavelli (1998, eq(3)), which was also used to fit the bulge of one Sd galaxy (ESO499 G37). The overall model is thus given by

$$\sigma(R) = \sigma_0 \exp(-1.678 \frac{R}{R_e}) + \sigma_1 (1 + \frac{R_c}{R})^\gamma \exp(-\frac{R}{R_s}) \quad (5)$$

The resulting profiles are also shown in Fig. 1, and the associated values of the parameters are given in Table 2. Except at radii less than about 2 pc, the fittings shown in Fig. 1 are quite satisfactory and are in agreement with HST observations. Recent HST observations, however, can not discriminate such a difference within about 2 pc, as we described above.

Table 2. The fitted values of parameters in (5)

M_{200}	σ_0	R_e	σ_1	R_c	γ	R_s
(M_\odot)	(M_\odot/pc^2)	(pc)	(M_\odot/pc^2)	(pc)		(pc)
$10^{12}h^{-1}$	127	361	317	8	2.2	23
3×10^{11}	146	327	212	18	1.7	27

The consistency between observations and simulations indicates that the dynamical evolution of SSCs proposed in this paper could be an explanation for the formation of exponential bulges with central stellar cusps for very late-type galaxies.

As mentioned above, the proportion of the bulges formed at 1 Gyr in the larger halo is significantly less than in the smaller halo, 65% vs. 90% . This is because larger halos have a stronger stripping effect on SSCs at a large distance from the center (due to their less centrally concentrated mass distribution), and, therefore, SSCs become less massive there, causing slower sinking to the bulge area. In a smaller halo, the SSCs can deposit more of their mass in the inner regions, as shown in Fig.2, resulting in more significant cusp components with R_c a factor of 2 larger than in the larger halo, as indicated in Table 2. The close correspondences between other parameters in Table 2 follow from the similarities of the NFS density profiles with different masses (Navarro et al. 1997).

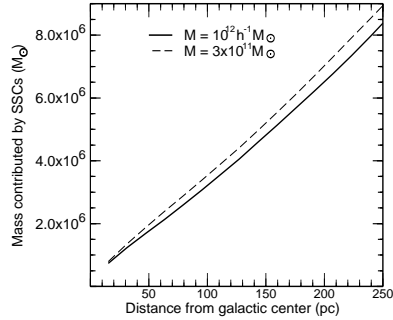


Figure 2. Mean mass profiles contributed by SSCs at 1 Gyr, showing different stripping effects of two DM density profiles adopted over bulge area

In order to see what could happen to the galaxies where no high-density central component is formed at 1 Gyr, we extend the simulation to 1.5 Gyr. The bulge formation rates are then increased to about 90% and 99% for the larger and smaller halos, respectively. This result implies that the proposed mechanism may be a viable mode for the formation of bulges and the nuclear star clusters.

The properties of the formed bulges, as shown in Fig. 1, are largely independent of the existence of IMBHs in SSCs, except for the region very near the galactic center (with radius of about 1 pc), as shown in Fig. 3. The difference arises because the tidal disruption cannot strip the SSC with only an IMBH left.

4 DISCUSSION

In our simulation, we have made some assumptions either due to the lack of information or for simplicity. An important assumption is that the background is composed of dark matter only, though we have considered the background variation later. Indeed, this assumption is compatible with what we investigate in this paper: the formation of bulges at the early stage. Accordingly, the SSCs we have studied are circumnuclear ones presumably originating from the mergers of very late-type galaxies. These galaxies have disk components only. In this case, the dark matter dominates over luminous systems at all radii. As a first step of our investigations it is reasonable to make such an assumption. On the other hand, it is

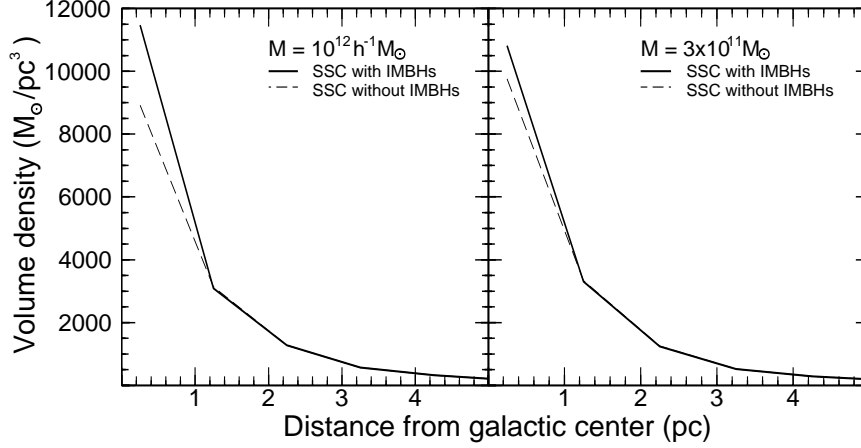


Figure 3. Volume densities contributed by SSCs with/without IMBHs for two adopted DM density profiles, indicating the differences of formed bulges at about 1 pc.

interesting to see what the theoretical prediction will be if more components are added, such as disks and a pre-existing bulge, in the background. The logical next step of our investigations is to study a way for the first-formed bulge to grow up further. Probably a new merger is needed. A new merger occurs between two disk galaxies with small bulges. A study of this kind is under our consideration.

As mentioned in Sect. 3, different halos will produce different bulge formation rates (more concentrated halos tend to be more effective in producing bulges). To try other halo models is under our consideration. Also, it would be very intriguing to consider a more realistic case, i.e., the one of halo variation incorporating several starbursts.

There would certainly be accumulated compact objects from the stripped inner part of the SSCs, as well as the remaining SSCs themselves—such as neutron stars, stellar BHs, or LMXBs with BHs—in the deep potential well of the galactic center. Whether these objects can form a BH at the galactic center is worth further study.

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